NASA-CR-200652

Attachment 2

Final Report
Order H-25925D

Advanced ORION Laser Concept

ADVANCED ORION LASER SYSTEM CONCEPT

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Introduction

The purpose of this brief study is to analyze the complete potential of the solid state laser in a very long pulse/high energy mode of operation as well as in a very short / lower energy mode of operation, operating in an actively-uncooled (termed "Hot-Rod" mode or "Heat Capacity" mode) method of operation. Concentrating on the phase aberrations to be expected by operating in such manner, the study presented here reports on estimating the bulk phase and intensity aberration distribution in the laser output beam during a single repped-pulse train. Recommendations are made for mitigating such aberrations.

Summary of Results; Conclusions and Recommendations

In this study, we have analyzed the optical performance of an uncooled solid state laser, and for reasons of reliability of performance, have chosen a slab-geometry, flashlamp-pumped MOPA design. In the pulse-width regime required (5-50 ns) the single pulse output fluences allowed by LLNL demonstrations, but degraded for repped operation, allow reasonable-shaped MO pulses to be amplified to the reuquireed energy level with little or no extraction-induced phase aberrations. Further, using LLNL data on thermal gain limitations, 100 -1000 pulses should be extractable from the laser device before gain reduction and other spectroscopic effects begin in the gain medium. At this point, optical pumping and lasing should be ceased, and cooling begun to return the medium to its original state. The analysis indicates that pump-nonuniformities and intrinsic gain medium nonuniformities will probably be the limiting causes of beam phase aberrations, as well as those in associated optical elements---all of which point to engineering design and perhaps adaptive optics to ameliorate those effects which cannot be eliminated by quality control and good engineering.

Statement of the Problem

In designing single-pulse solid-state uncooled lasers, the concentration typically is on the extraction of maximum single-pulse energy at the desired pulse width with the desired beam average phase uniformity. In designing repetitively -pulsed solid-state actively-cooled lasers, the concentration is typically on the extraction of maximum long-term average power at the given pulse width and desired pulse repetition rate, all with the desired beam average phase uniformity.

In the present study, however, the concentration is on the design of uncooled solid-state lasers with the extraction of maximum total emitted laser energy (single-pulse energy X pulse rep rate X run-time) with a specified pulse width and with minimum area-integrated beam phase aberration, all with an eye toward systems which can be cooled down relatively quickly to repeat this repped-pulse lasing cycle in a reasonably fast turn-around time.

Method of Approach

In this analysis, we :

1. first lay out the alternatives to the modes of operation
   - geometry of the gain medium (slab vs rod)
   -amplifier vs oscillator operation
2. then outline the key issues affecting the present problem

3. then discuss heat deposition and its effects on phase differences across the beam
4. then analyze the sources of phase aberration in the output beam, and
5. finally identify potential mitigation approaches

Technical Analysis

A) Mode of Operation

Figure 1 shows the basic geometries of solid-state lasers :

1. rod gain medium :axial extraction, radial pumping, radial cooling
2. slab gain medium: long-dimension extraction, short-dimension pumping and cooling
3. slab gain medium: Brewster's-angle extraction and pumping, short-dimension cooling

Figure 2 shows the laser design trade-off parameters . One of the important parameters is the maximum extractable fluence (joules/cm^2 of output) which the gain medium material can handle without important irreversible damage in bulk or at the surface. The current values of maximum damage threshold for SINGLE-PULSE operation at various pulse-widths are showing **Figure 3.** Note that in the region attractive to ORION (5 to 50 ns) the allowable output fluence at 1.06 microns is between 10 and 20 joules/cm^2 for glass and YAG hosts doped with Nd ions.

It is well known for both gas lasers and solid-state lasers, that oscillator or resonator extraction techniques produce the highest extraction efficiency and the most compact and lighter-weight laser designs, while master-oscillator/power-amplifier (MOPA) extraction techniques can provide higher beam quality, more flexibility and tighter control of the output waveform and phase / frequency content of the output beam at the price of larger, heavier and more cumbersome laser system designs.

SINCE MINIMIZING FLOOR-SPACE AND WEIGHT IS NOT AN OVER-RIDING CONSIDERATION FOR THE GROUND-BASED ORION CONCEPT, WHILE MAXIMUM FLEXIBILITY AND CONTROL AT HIGH BEAM QUALITY IS OF UTMOST IMPORTANCE, WE HAVE CHOSEN THE MOPA AS OUR RECOMMENDED LASER ARCHITECTURE.

The next mode of operation to be chosen is the cooled vs uncooled version of the solid state laser. Clearly for single-pulse operation, no cooling is considered. For rep-rated operation however, whether to cool or not IS an issue. Clearly for continuous 24 hrs / day operation, we require active cooling. However, for an operating mode where one 30 second debris engagement occurs every 10 minutes or so in one two-hour period at dawn and another at dusk (a very real possibility for a viable near-term system), one must question whether ACTIVE cooling is necessary during lasing, or just a rapid cooldown between shots. These two operating scenarios can result in VERY different laser designs, with the former (active cooling while lasing) being a MUCH more difficult (and hence time-consuming and hence expensive) laser design than a simpler, cheaper and potentially more robust system which simply needs to be cooled down between bursts. It is the latter system which is discussed in this report.

B) Key Issues

Figure 4 lists the issues which must be considered in any solid-state laser design as to damage, performance as a simple laser energy source, and performance as a source of coherent radiation.
We assume in this report that issues of damage and performance as an energy source are taken care of by good engineering design. We discuss her those issues concerning beam quality, especially those important to an active optical system whose function it is to compensate for these in real time, either open-loop (by pre-programming) or in closed-loop operation using sensors and feedback loops.

FIG 1

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Northeast Science & Technology Repped Solid State Geometries

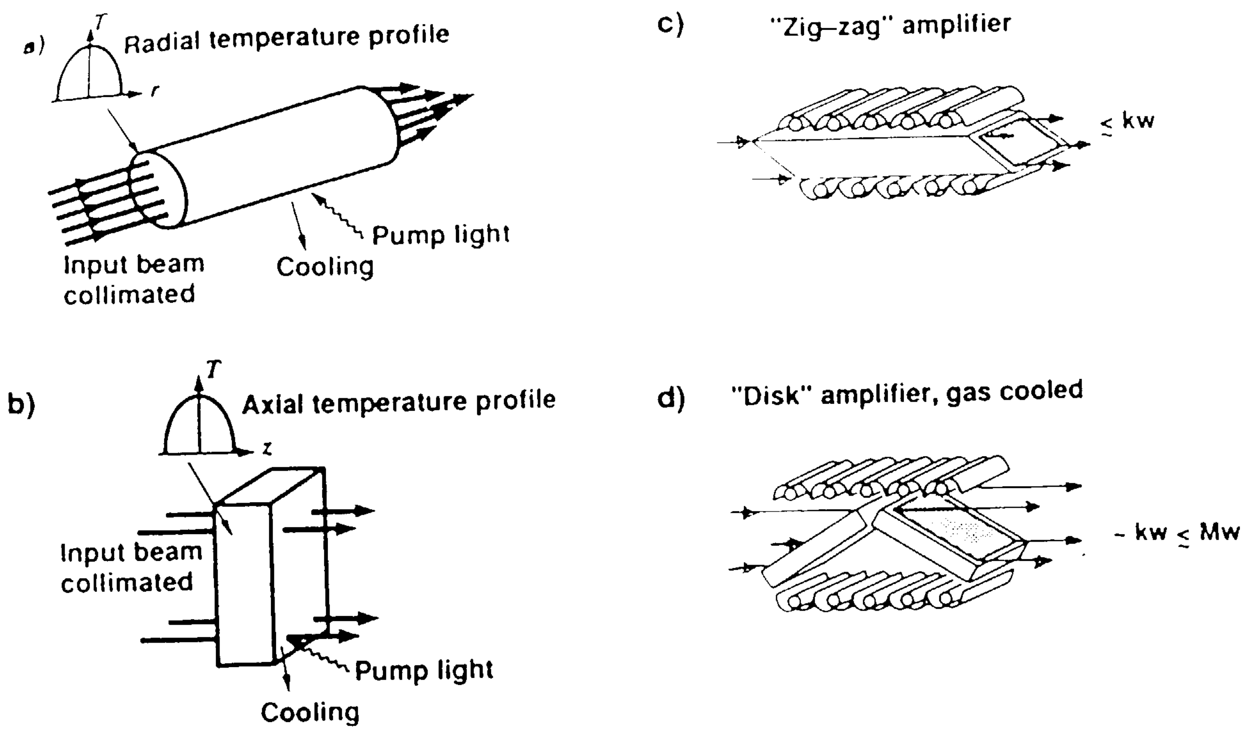

FIG 2

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SOLID STATE LASER DESIGN TRADE-OFF PARAMETERS

Material Damage Limits pulsed Joule/cm^2 and watt/cm^2 of output. Both scale with pulse length

Pump-Radiation Attenuation Scales gain medium cross-section dimensions and doping fraction

Above parameters limit maximum energy per pulse

Gain Parasitics Limit cavity length at achievable small signal gain

Crystal Fracture Limits mean temperature rise for a given material. Beam quality degrades before rods fracture.

Optical Path (temperature) In homogeneities Limits temperature "ripple" for allowable cavity length

Thermal Diffusion / Conduction Limit pulse repetition rate for required temperature uniformity which drives phase uniformity

Upper State Natural Decay Rates Limit maximum rep rate for raw power output (may not be high-quality beam)

Above parameters dictate maximum rep rate

System Efficiencies Drive power and energy requirements

Platform Payload Capacity Limits allowable weight, volume and consumables

No Limit to Run Time For steady-state-cooling designs

FIG 3

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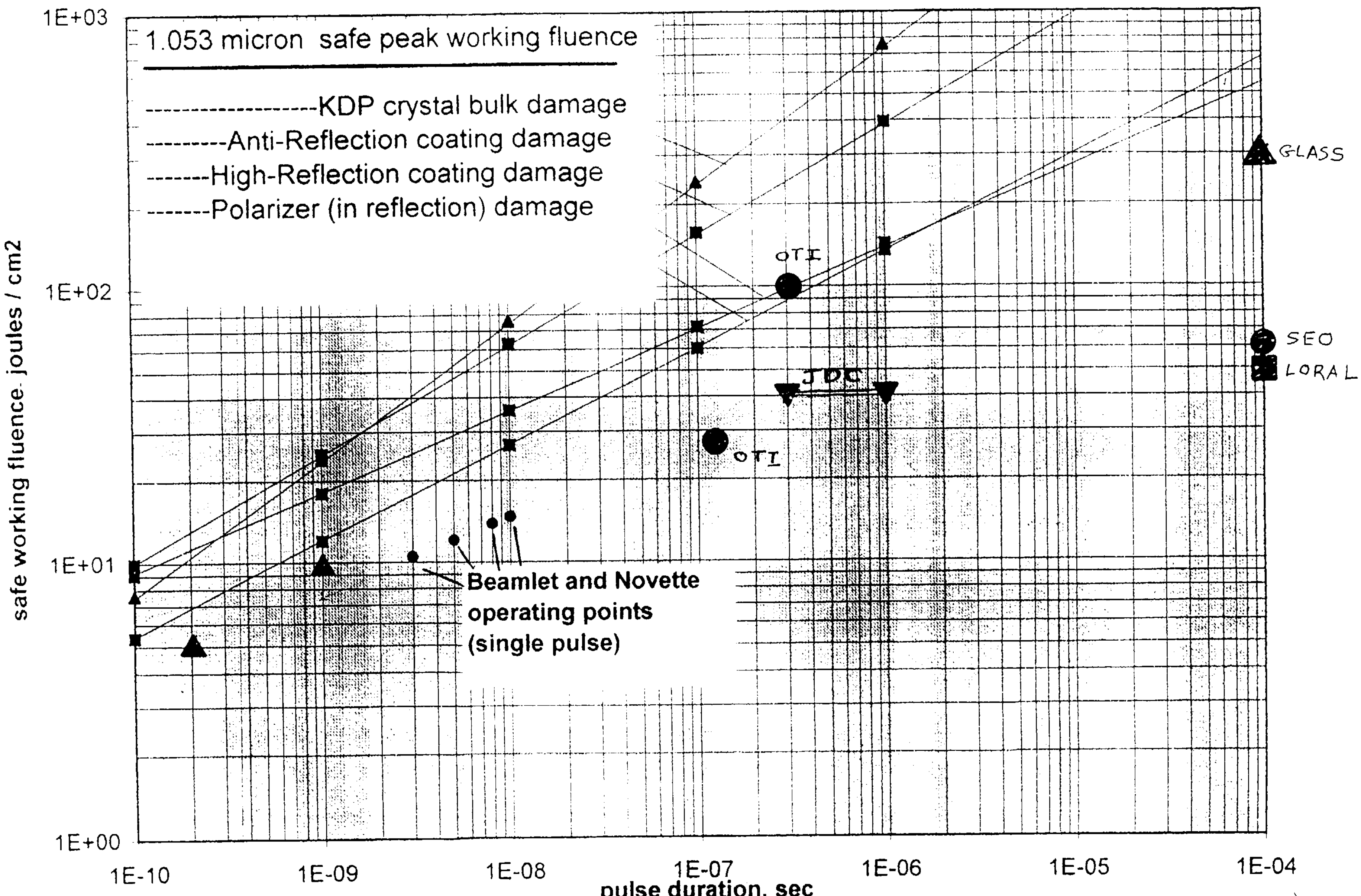
Limiting Single Pulse Fluence in ND:Glass Beamlet Train



LLNL Beamlet and Novette Lasers have Demonstrated 10-20 j/cm^2 Optics

FIG 4

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Northeast Science & Technology **Rep-rate issues for Solid State Lasers**

Damage limits stemming from Thermal Deposition and Inadequate Thermal Management

Fracture — differential thermal profile buildup induces-- tension in outer (free) edges
-- compression in center (free) region

Differential Expansion — between gain mat'l and transmission-face coatings as well as edge-band coatings

Inclusions / Interfaces — surface and bulk sites show --higher linear absorption than bulk deposition, and/or
--higher electric field concentrations with local heating higher than bulk deposition

Phase Aberrations resulting from *Differential* Thermal Deposition

Thermally-induced phase shifts- change of index of refraction with temperature
- thermal expansion induces different physical path lengths for optical raypaths

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Photoelastic — stress-induced changes in refractive index at laser wavelength

Thermal Lensing — symmetrical thermal change in refractive index causes whole-beam divergence

Stress Bi-Refringence — stress-induced changes in refractive index over range of wavelengths

Beam Steering — asymmetric thermal changes in refractive index causes beam steering

Performance Limits due to *Absolute* Temperature Levels Reached

Redistribution of Population among Stark levels (ie, gain is a function of temperature level)

Resonance Re-Absorption (more important at high gain values and high absolute temperature levels)

Line-Width Dependence on Temperature Level (higher temperatures mean wider linewidths)

C) Heat Deposition Analysis

The discussion of heat deposition in the solid state laser is dominated by the line spectrum of the absorption by the solid state laser's gain medium convolved with the power spectrum of the pump source, and to a lesser extent the design of the optical cavity which traps (or does not trap) the pump radiation for ultimate absorption by the gain medium. The conventional mode of operation fro small lasers and/or CW lasers is to use efficient CW Diode lasers as pump sources. Because the CW diode laser is tuned exactly to the desired absorption bands in the solid state laser, waste heat is limited to quantum efficiency effects in the pumped solid-state laser. However, these CW diode lasers are too low in power to pump the multi-kilojoule lasers required for ORION, so we are left with the conventional pump sources ---dominated by doped Xenon flashlamps. **Figure 5 (ref 1)** shows typical energy deposition fractions compared to typical laser extraction. Perhaps only 8% of the input lamp power is absorbed by the laser gain medium, and only 2% of the input lamp energy appears as output laser energy. Hence, this figure would indicate that of the deposited energy in the solid state medium, 25% is emitted as radiation and 75% remains as heat. **Figure 6 and 7 (from refs. 2,3 and 4)** show more recent achievements in efficiencies, including the additional efficiency levels for cooled systems, either real-time actively-cooled or between-burst cooling as is discussed here. Note the efficiencies for diode pumping in **Figure 7**, and summarized below.

Pump Scheme	Diode Pump	Flashlamp Pump
Electrical Power Into Pump	100 units (U)	100 U
Power Absorbed by Laser	70 U-90 U	50 U-75 U
Power emitted by laser	1 U-14 U	0.3 U - 7 U
Power Remaining as Heat	50 U- 90 U	45 U - 75 U

It is these inefficiencies which must be addressed in the laser design , because it is the waste heat LEVEL and its DISTRIBUTION which dictate the phase aberrations produced in the beam. Note however, that the differences in diode pumping and flashlamp pumping are minimal as far as phase aberrations go. The major difference is in the size and complexity of the power supplies which power them.

Figure 8 sketches the energy level diagram for 3-level and 4-level solid state lasers., and sets the nomenclature for the gain terms. **Figure 9** sketched the thermal profiles in an amplifier stage which is ***relatively*** well-filled with laser intensity, but which (as it must) has zero intensity near the edges of the gain medium. Note the thermal profiles immediately after the extraction and the slower-timescale deposition (leakage) between extraction pulses due to the slow upper-state decay which being excited by the pump light. **Figure 10** shows the expressions for the time-dependent heat deposition in the solid state laser medium. **Figures 11 and 12** list the equations used here to analyze the time-dependent thermal profiles . **Figure 13** shows the temperature change all along the optical axis of the final amplifier stage immediately after an extraction pulse. Clearly, the more solid medium is used (ie, the longer the gain medium "L") the less is the temperature change, because of the increased heat capacity of the laser medium . After the extraction, heat continues to be deposited, because of the finite-rate leakage out of the upper states of the laser medium between pulses. **Figure 14** shows the temperature change all along the optical axis of the last amplifier stage JUST BEFORE the next extraction pulse (when the gain has been pumped up to design value). In the next Section, we will use these temperature changes to scope the requirements on beam phase homogeneity.

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System Efficiency Drives Power Supply Cost

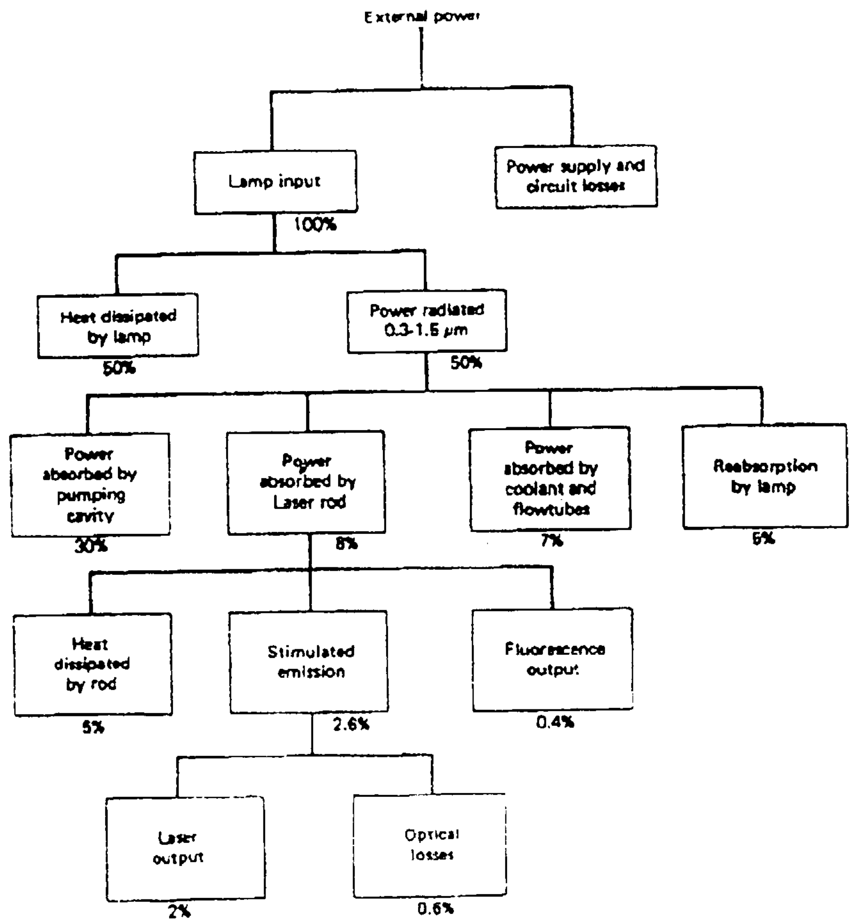

Fig. 6.75. Energy balance in an optically pumped solid-state laser system. (The percentages are fractions of electrical energy supplied to the lamp)

FIG 6

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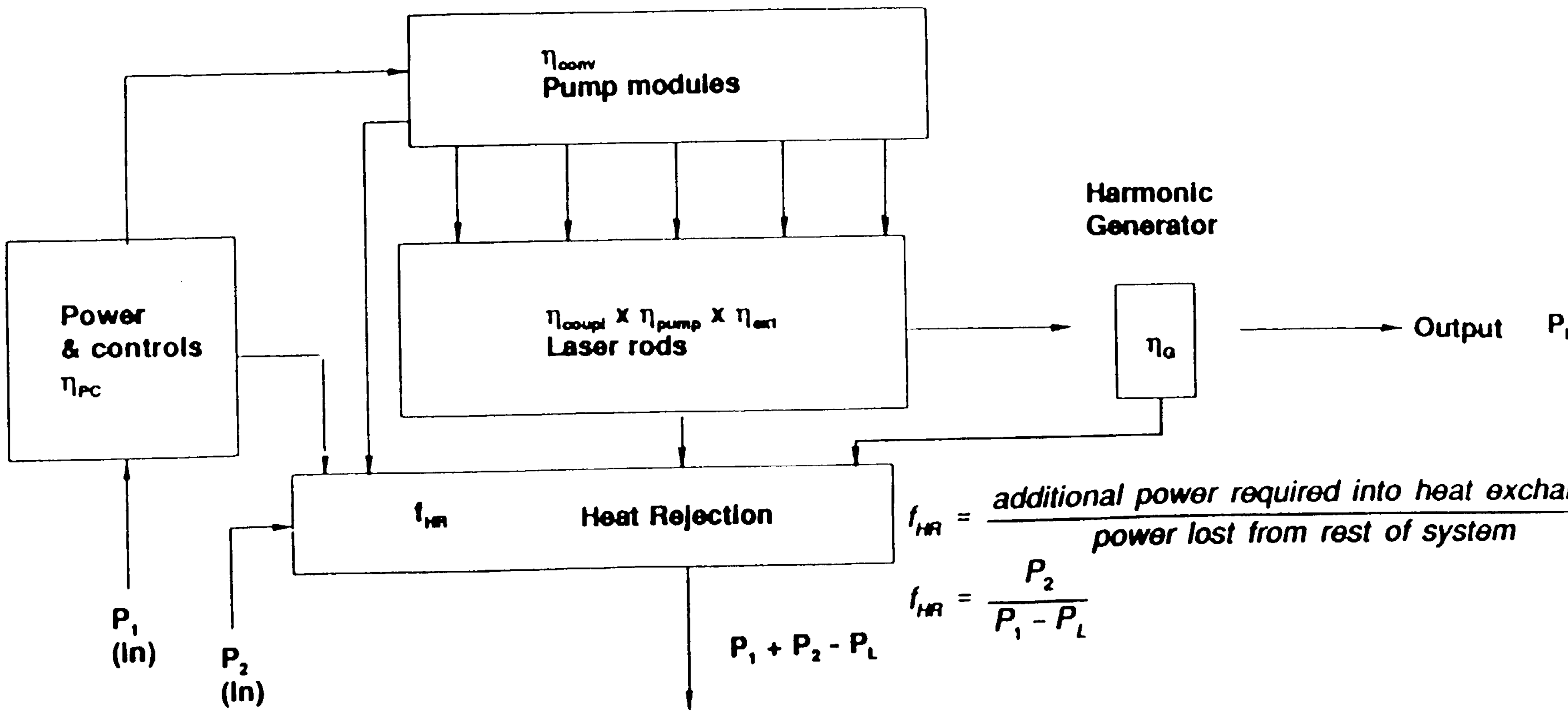
SOLID STATE SYSTEM EFFICIENCY



$$f_{HR} = \frac{\text{additional power required into heat exchange}}{\text{power lost from rest of system}}$$

$$f_{HR} = \frac{P_2}{P_1 - P_L}$$

$$\eta_{tot} = \frac{\text{laser power out}}{\text{total power in}} = \frac{P_L}{P_1 + P_2} = \frac{P_1 \times \eta_{PC}\,\eta_{conv}\,\eta_{coupl}\,\eta_{pump}\,\eta_{ext}\,\eta_G}{P_1 + P_1(1 - \eta_{PC}\,\eta_{conv}\,\eta_{coupl}\,\eta_{pump}\,\eta_{ext}\,\eta_G)\,(1 + f_{HR})}$$

FIG 7

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DIODE-PUMPED SOLID-STATE LASER SYSTEM EFFICIENCY AND TYPICAL VALUES

$$\eta_{total} = \frac{\eta_{PC}\ \eta_{conv}\ \eta_{coupl}\ \eta_{ext}\ \eta_{G}}{1 + (1 - \eta_{PC}\ \eta_{conv}\ \eta_{coupl}\ \eta_{pump}\ \eta_{ext}\ \eta_{G})\ (1 + f_{HR})}$$

Heat rejection
50%-90% efficiency
($0.1 \leq f_{HR} < 0.5$)

Harmonic generation
40%-70%

Extraction
70%-90%

Absorbed pump x quantum effic. x Stokes shift
(70%-90%) x 90% x 76%

Optical coupling
70%-90%

System range
1.1%-14.1%

Conversion to diode output in pump band
30%-50%

Power conditioning and controls
80%-90%

Diode conversion and heat rejection efficiency show biggest payoff potential for system efficiency

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SCALING SOLID STATE LASER

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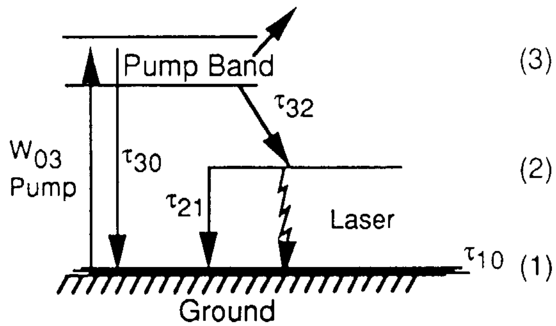
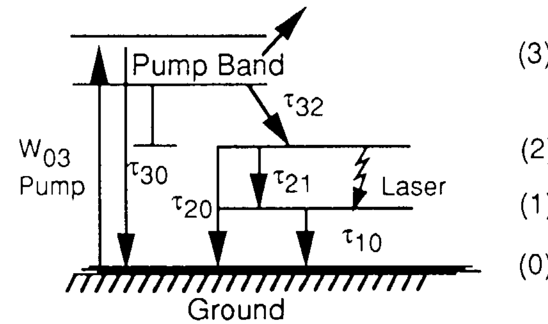
Three Level System



Example: Ruby ($\lambda = 0.63$)
H_o in YAG, YLF ($\lambda = 2\ \mu m$)

Four Level System



Example: N_D in YAG, YLF ($\lambda = 1.06\ \mu m$)
($\lambda = 2\ \mu m$)

Small signal gain $$g_o = \sigma_{21}\, \eta_{tot} \frac{W_{03}\tau_{21} - g_2/g_1}{W_{03}\tau_{21} + 1}$$

$$g_o = \sigma_{21}\, \eta_{tot} \left(\frac{W_{03}\tau_{21}}{W_{03}\tau_{21} + 1} \right)$$

Requires $\geq$ 50% of ground level of ruby must be exited
- τ_{32} fast (1-2 ns)
- τ_{21} slow (500 μsec) (Ho:YLF)
- τ_{10} very fast (< 1 ns)

Typically, $W_{03}\,\tau_{21} \leq 10^{-2}$ (YAG) (slow pump, fast pulse)
- τ_{32} fast (1-2 ns)
- τ_{21} slow (250 μsec) (N_D)
- τ_{100} fast (1-10 ns)

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AMPLIFIER THERMAL INHOMOGENEITIES

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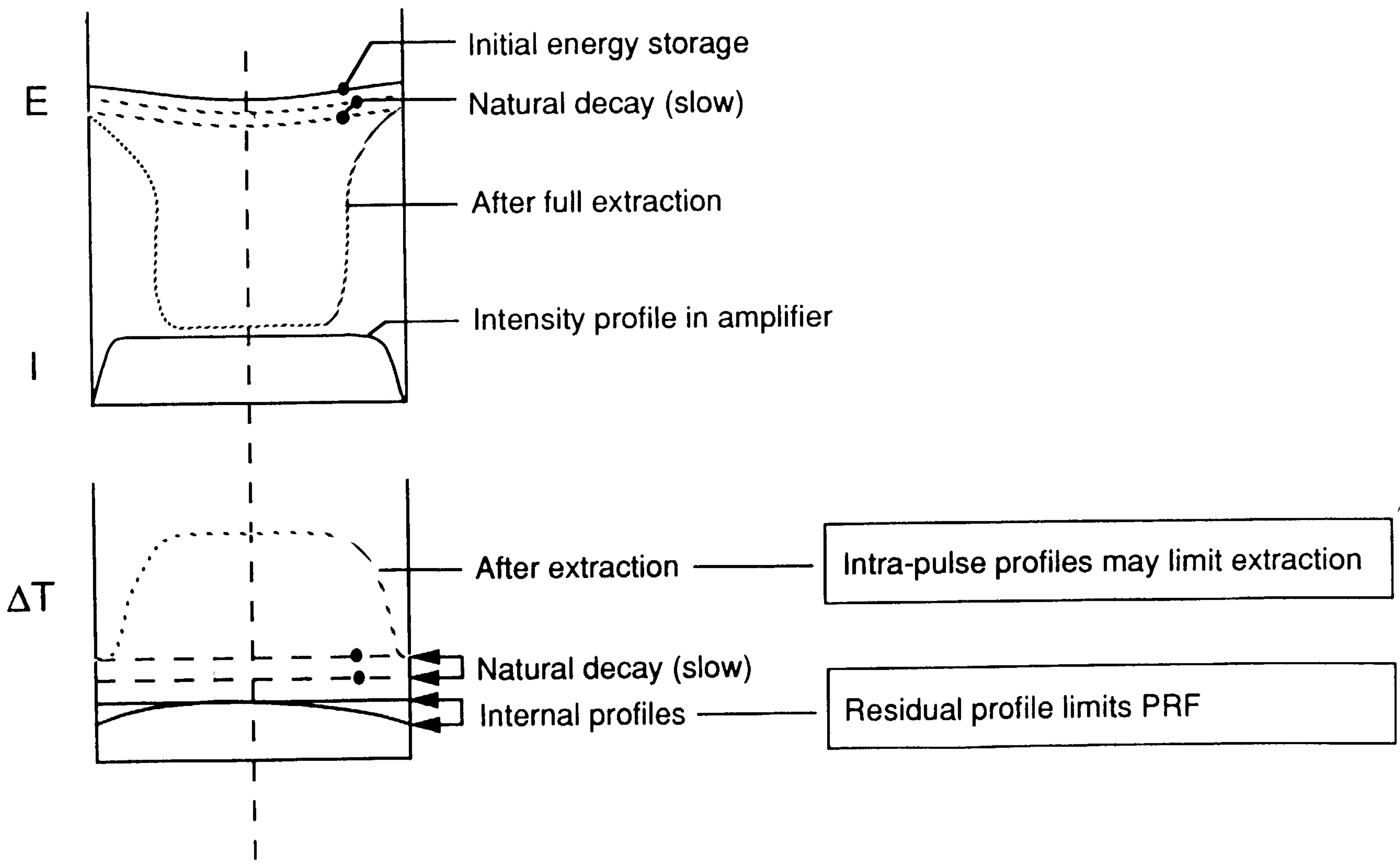

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FIG 10

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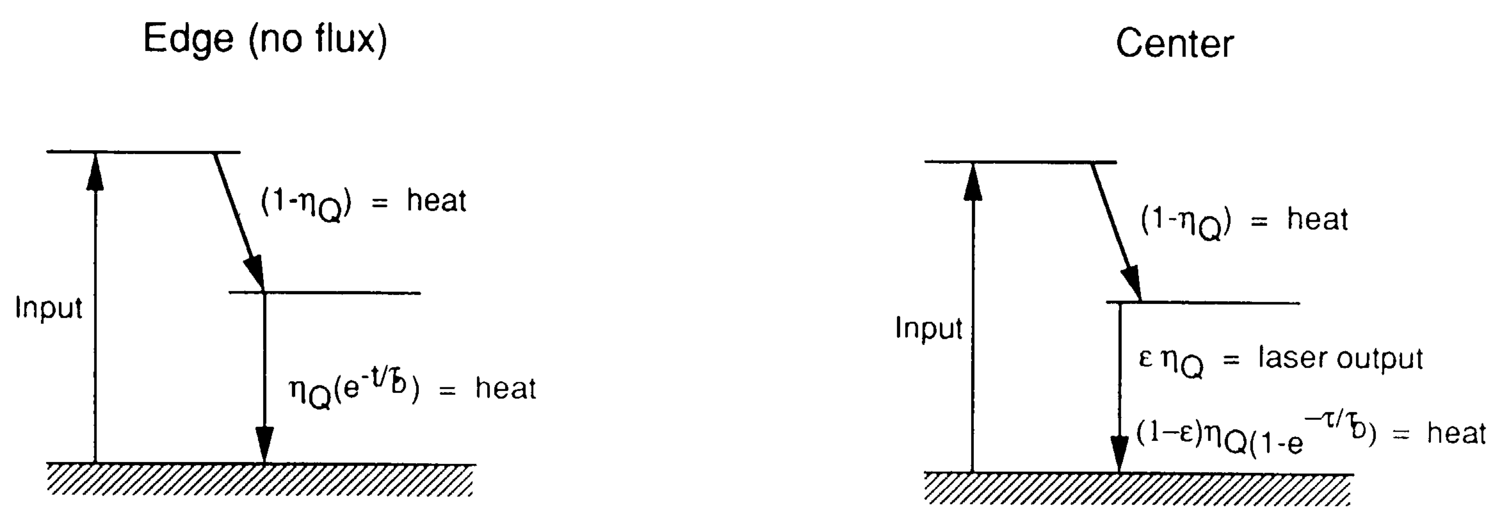
DOMINANT THERMAL RELAXATION PROCESSES IN SOLID STATE LASER



- Quantum inefficiency $(1-\eta_Q)$ appears "instantly" as heat
- Upper laser state
  - Extracted energy $(\varepsilon\,\eta_Q)$ leaves "instantly"
  - Un-extracted energy $((1-\varepsilon)\eta_Q)$ relaxes slowly into heat

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AMPLIFIER HEATING ON A SINGLE PULSE

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- Heating of amplifier during pump pulse

$$\rho\ C\ \frac{d\,T_1}{dt} = N_{upper}\ E_{upper}\ \frac{1}{\tau_D} + (1 - \eta_Q)\ P_{pump}$$

$$@\ \frac{d}{dt}(N_{upper}\ E_{upper}) = \eta_Q\ P_{pump} - (N_{upper}\ E_{upper})/\tau_D$$

Note: $E_{stored} = N_{upper}\ E_{upper} = \eta_Q\ P_{pump}\ \tau_D\ (1 - e^{-t_{pump}/\tau_D})$

For a constant pump power during pump pulse t_{pump}

$$\rho\ C\ \Delta T_1 = \eta_Q\ P_{pump}\ \tau_D \left(\frac{t_{pump}}{T_D} - e^{-\frac{t_{pump}}{T_D}} \right) + (1 - \eta_Q)\ P_{pump}\ t_{pump}$$

Note: $t_{pump} \leq \tau_D$ for minimum pump input energy efficiency and minimum heating

- Heating of amplifier after amplifier extraction and subsequent decay of remaining upper state

$$\rho\ C\ \Delta T_2 = \left(\frac{E_{stored}}{\eta_Q} - \frac{J_{out}}{\eta_Q L} \right) (1 - e^{-t/\tau_D}) + \left(\frac{1 - \eta_Q}{\eta_Q} \right) \frac{J_{out}}{L}$$

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AMPLIFIER HEATING FOR REPPED-PULSE AMPLIFIERS

Amplifier designed to be operated when gain has reached design level for each pulse

$$g_o = \beta\ E_{storage} = \beta\ N_{upper}\ \hbar\nu = \beta\ \eta_Q\ P_{pump}\ \tau_D\ (1 - e^{-t/\tau_D}) \rightarrow \beta\ \eta_Q\ P_{pump}\ t_{pump}\ (t_{pump} << \tau_D)$$

- Heating of amplifier during pump phase

$$\rho\ C\ \Delta T_1 = P_{pump}\ t_{pump}\ (1 - \eta_Q\ e^{-t_{pump}/\tau_D}) \rightarrow P_{pump}\ t_{pump}\ (1 - \eta_Q)\ (t_{pulse} << \tau_D)$$

- Heating of amplifier due to extraction and natural decay during interpulse time

$$\rho\ C\ \Delta T_2 = \frac{1}{\eta_Q}(1 - \eta_Q)\frac{J_{out}}{L} + \frac{1}{\eta_Q}\left[E_{stored} - \frac{J_{out}}{L}\right][1 - e^{-t/\tau_D}]_{interpulse}$$

$$\rightarrow \frac{E_{stored}}{\eta_Q} - \frac{J_{out}}{L} \qquad (t_{interpulse} >> \tau_D)$$

Bulk heating

$$\boxed{\Delta T = \Delta T_1 + \Delta T_2 = \frac{1}{\rho C}\left[\underbrace{\frac{g_o}{\beta\eta_Q}(1 - \eta_Q)}_{\text{pump phase}} + \underbrace{\left(\frac{g_o}{\beta\eta_Q} - \frac{J_{out}}{L}\right)}_{\text{extraction decay}}\right]}$$

Max radial difference

$$\boxed{\Delta T^*\ (center\ to\ edge) = \frac{1}{\rho C}\frac{g_o}{\beta\eta_Q}(2 - \eta_Q)}$$

FIG 13

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BULK AND RADIAL ΔT DURING EXTRACTION PULSE

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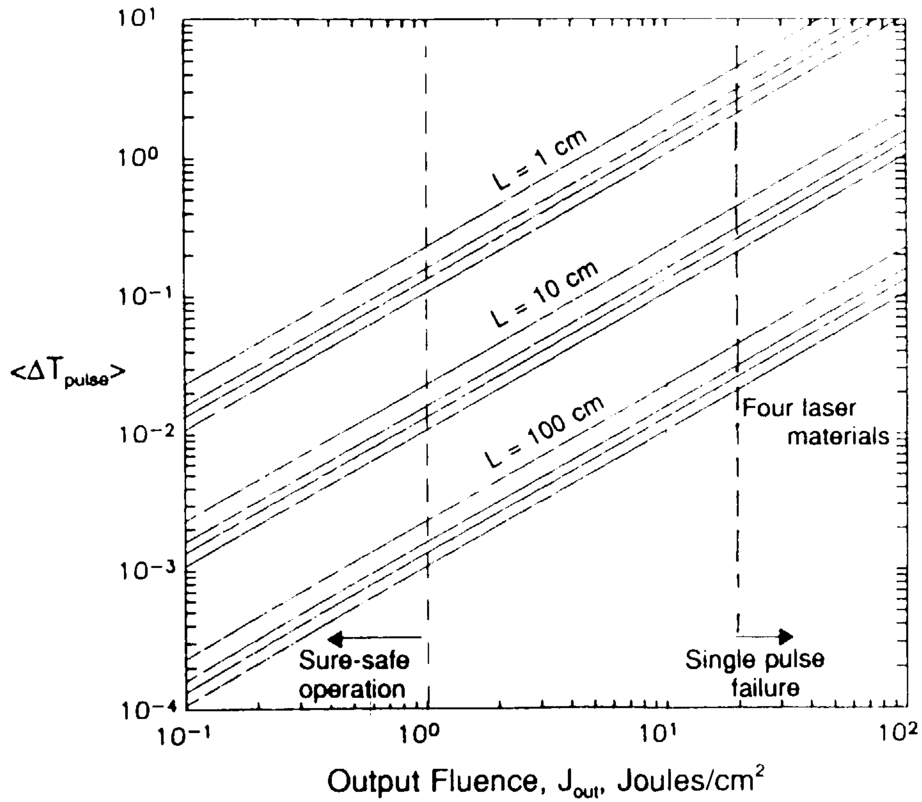

During extraction pulse

$$\Delta T_{pulse} = \frac{1}{\rho C} \frac{J_{out}}{L} \frac{1 - \eta_Q}{\eta_Q}$$

- occurs during output pulse
- results in bulk optical path change in center
- no extraction near edge implies
  $\Delta T = 0$
  $\Delta T_{radial} = \Delta T_{bulk}$

L = TOTAL PHYSICAL GAIN MEDIUM LENGTH IN OPTICAL DIRECTION IN FINAL AMPLIFIER STAGE

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FIG 14

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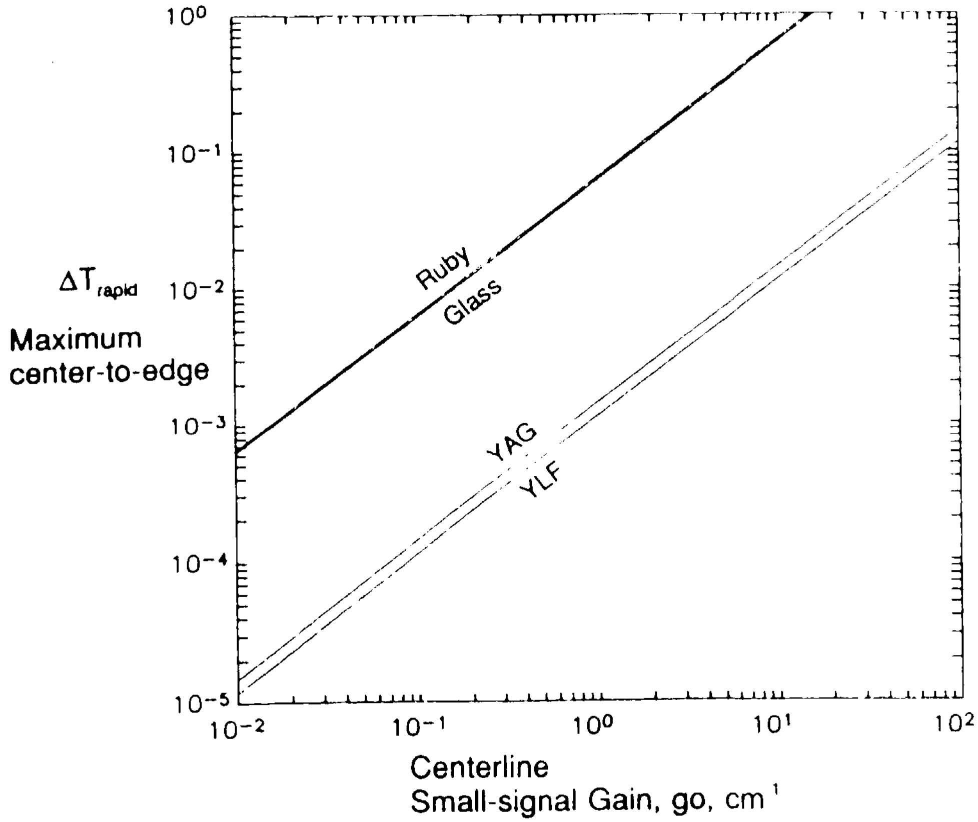
RADIAL ΔT IN AMPLIFIER BETWEEN PULSES



$$\Delta T_{max} = \frac{1}{\rho C} \frac{g_o}{\beta \eta_Q} (2 - \eta_Q)$$

- occurs between output pulses
- assumes no extraction near edge of MO beam

	ρC	β	η_Q
Phosphate glass	2.68x.168	0.16 cm^2/J	75%
Ruby	0.42/0.13	0.088	70%
N_D:YAG	4.56x0.59	4.73	65%
HO:YLF	3.95x0.79	0.5	75%

D) Phase Aberration Analysis

Figure 15 shows the relations which give rise to phase inomogeneities $\Delta\Psi$ --the temperature-dependent index of refraction of the gain medium and its thermal expansion (ie physical length growth) due to heating in the center of the medium as compared to the region near the edge of the medium which has been pumped optically just as hard as the center, but has had no laser extraction (so it will tend to get hotter than the center after upper-state relaxation to ground). **Figure 16** shows the phase difference between the optical axis and the medium edge resulting from various ΔT's along various length gain media. *The very simple relation tells a very powerful story* -- keep either the temperature difference between center and edge very small (ie DO NOT COOL, and FILL THE GAIN MEDIUM) or keep the medium very short. Or both. A value of $\Delta\Psi$ of 0.3 keeps the far-field intensity within 10% of that of a diffraction-limited beam. The simple formula below described this relationship.

$$I / Io = 1/(1+(\Delta\Psi)^2)$$

Figure 17 uses $\Delta\Psi = 0.3$ as a limit, and relates the temperature rise in the slab center to the extracted single-pulse fluence. For Nd Yag, up to 20 joules /cm^2 are allowed (ie UP TO MATERIAL DAMAGE THRESHOLDS !!!) before the temperature differences are noticeable. If we limit the beam to the 1-20 joules/cm^2 region, no gross extraction effects should be seen in uncooled amplifiers. The major thermal differences will therefor be dominated by pump uniformity --that is good engineering of the pump lamps and their optical cavities. Another cut at this conclusion is shown in **Figure 18**, which indicates that flat-top (or equivalently super-gaussian shaped) amplifier pulses are not required for radial thermal uniformity at the 10 joule/cm^2 output level.

As to temperature level, the "Hot Rod"(**ref 4**) or "Heat Capacity Mode" (**ref 5**) or Thermal Inertial Laser" (**ref 3**) methods of operation ----all equivalent ,simply different names given to the same concept--- has very reasonable upper temperature-level limits before the gain begins to decrease. **Figure 19** shows the centerline temperature rise after a single pulse as functions of the gain slab thickness and pump pulse irradiance. Clearly, the more solid gain medium we have (ie the thicker the slab) the less the temperature rise produces in the slab by the given energy delivery. The LLNL Beamlet laser and others at LLNL used as models in this study pump in the region 0.2 to 2 joules of pump light per square cm of slab surface area, have been successful cooling this energy density with active gas or liquid flows for truly-continuous repetititve-pulse operation of Beamlet laser designs for the National Ignition Facility **(Ref 7)**. **Figure 20** shows the successfully-demonstrated cooling rates on laser slabs at LLNL and the operational laser slab optical pumping heat loadings at LLNL (**Refs 6 & 7**) , and the implication for CONTINUOUS rep-rated operation of the Beamlet laser, and this bodes well for cool-down between bursts for the "Hot-Rod" mode of operation. Using these pump fluence levels and gain slabs in the 0.5 to 2 cm thick region will produce small (0.1-1 $^{\circ}$C) termperature rises in the slabs for each pulse. This temperature rise per pulse will allow 100 to 1000 pulses to be emitted from the UNCOOLED medium until the temperature level of 350 K to 400K (**ref 6**) is reached, where gain reduction begins as well as Stark level redistribution, resonant re-absorption and line spreading (mentioned in **Figure 4** as considerations) begin to become important (**ref 5** , where 390 K is recommended as an upper limit)

Conclusions

In the above, we have analyzed the optical performance of an uncooled solid state laser, and for reasons of reliability of performance, have chosen a slab-geometry, flashlamp-pumped MOPA design. In the pulse-width regime required (5-50 ns) the single pulse output fluences allowed by LLNL demonstrations, but degraded for repped operation, allow reasonable-shaped MO pulses to be amplified to the reuquireed energy level with little or no extraction-induced phase aberrations. Further, using LLNL data on thermal gain limitations, 100 -1000 pulses should be extractable from the laser device

FIG 15

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LIMITS ON BEAM PHASE HOMOGENEITY

W.J. Schafer Associates

- **Assume**
  - perfect pump-light irradiation of entire crystal
  - only quantum defect inefficiency appears as heat

$$\left.\begin{matrix} E_{lasing} \lesssim 0.76\ E_{absorbed} \\ E_{heat} \geq 0.24\ E_{absorbed} \end{matrix}\right\rangle E_{heat} > 0.32\ E_{lasing}$$

  - resonator configuration <u>not</u> used because strong radial internal flux gradients cause strong local dn/dt values even with variable reflectivity outcoupling
  - amplifier configuration using super Gaussians allows <u>small</u> radial gradients

- **RMS phase non-uniformity given by**

$$\langle\Delta\psi\rangle = \frac{2\pi}{\lambda}\left(\frac{dn}{dT} + (n-1)\alpha\right) L\ \langle\Delta T\rangle$$

- **RMS thermal non-uniformity given by heat balance**

$$E_{heat} + \rho\, C\, \Delta T_{bulk}\, \pi R^2 L \geq 0.32\ E_{laser} = 0.32\ J\pi R^2$$

$$\Delta T\big|_{bulk} L = \frac{\geq 0.32\ J_{output}}{\rho C}$$

$$\boxed{\langle\Delta\psi\rangle = \frac{2\pi}{\lambda}\left(\frac{dn}{dT} + (n-1)\alpha\right)\left(0.32\ \frac{J_{out}}{\rho C}\right)\frac{\langle\Delta T\rangle}{\langle\Delta T\rangle_{bulk}}}$$

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FIG 16

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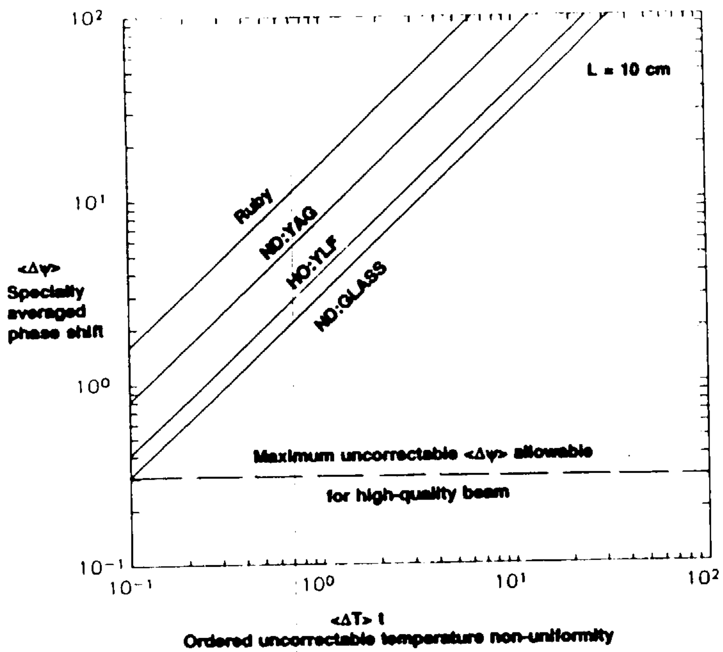
THERMAL MANAGEMENT IN SOLID STATE LASER MEDIUM



Phase shift due to optical path difference

$$\langle \Delta\psi \rangle = \frac{2\pi}{\lambda}\left[\frac{dn}{dT} + (n-1)\alpha\right] L\langle \Delta T \rangle$$

For near-perfect beam, ($I/I_o > 0.90$) require small phase shift in medium:

$$\langle \Delta\psi \rangle \leq 0.3$$

	λ	$\frac{dn}{dT}$*	α*	D Thermal Diffusion Coefficient
Ruby	**0.69 μm**	**13×10^{-6}/°C**	**6×10^{-6}/°C**	**0.13 cm^2/S**
ND:YAG	**1.06 μm**	**7×10^{-6}/°C**	**8×10^{-6}/°C**	**0.05 cm^2/S**
ND:phosphate glass	**1.06 μm**	**2-3×10^{-6}/°C**	**9.8×10^{-6}/°C**	**0.006 cm^2/S**
HO:YLF	**2.1 μm**	**7×10^{-6}**	**8×10^{-6}**	**~0.05 cm^2/S**

Because of longer wavelength, holmium (2 μm) lasers can handle more heat deposition than YAG
Because of faster thermal diffusion, Holmium-YLF and ND:YAG have higher PRF than glass host materials

*Ref. Koechner, "Solid State Laser Engineering"

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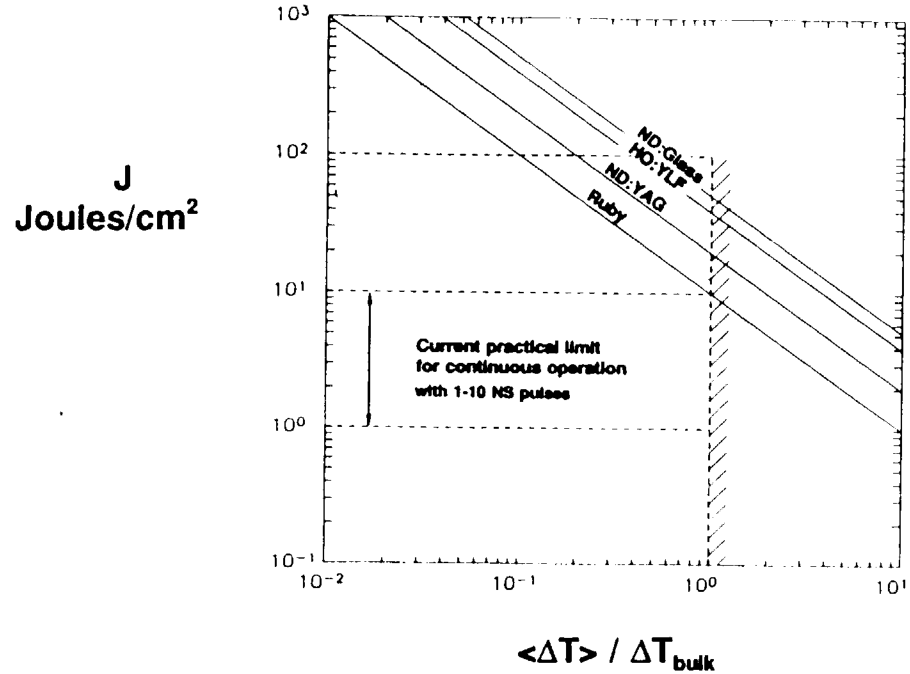
GOOD QUALITY BEAM - USABLE OUTPUT FLUENCES



Temperature "ripple" in laser rod prior to next pulse/peak bulk temperature rise after pulse extraction

$$0.3 = \frac{2\pi}{\lambda}\left(\frac{dn}{dT} + (n-1)\alpha\right)\frac{\langle \Delta T\rangle}{\langle \Delta T_{bulk}\rangle}\left(\frac{0.32\,J}{\rho C}\right)$$

- Output fluence from amplifier limited by surface damage, small phase in homogeneity and quantum defect heating

- Quantum-defect heating <u>allows</u> higher output fluences than current output reflector surface damage limits
- Output fluence limited by <u>surface damage</u>, not medium heating and phase shifts

FIG 18

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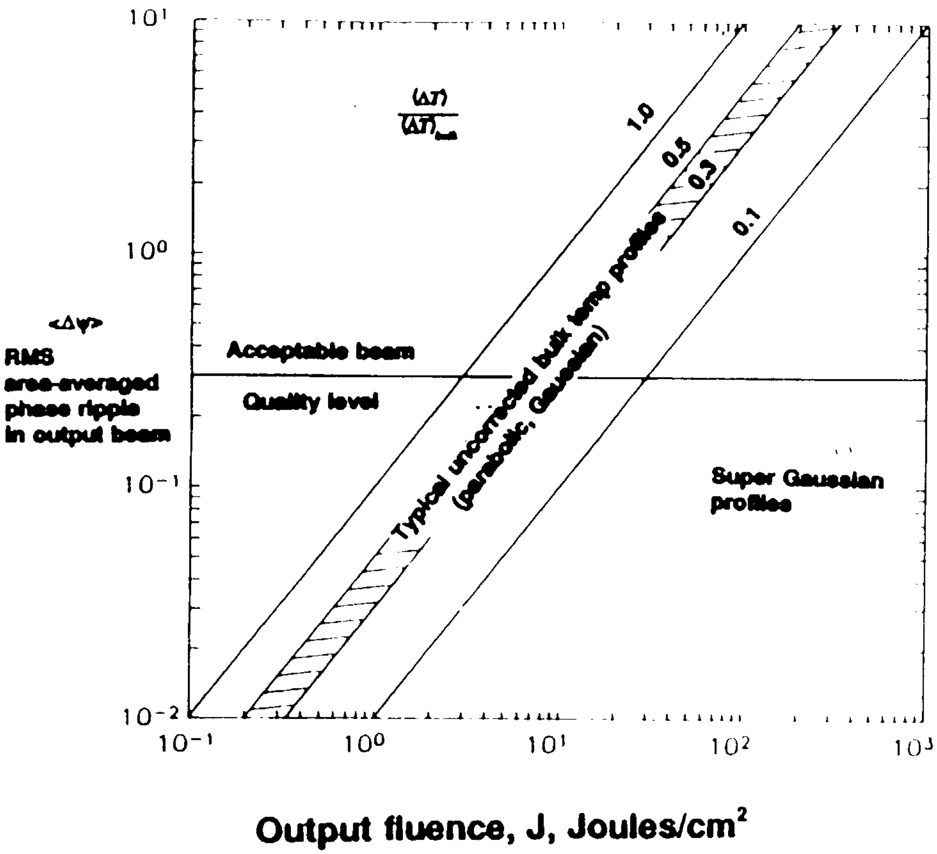
AMPLIFIER OUTPUT - BEAM PHASE HOMOGENEITY

W.J. Schafer Associates



$$\langle\Delta\psi\rangle = \frac{2\pi}{\lambda}\langle\Delta(nL)\rangle$$

$$\simeq \frac{2\pi}{\lambda}\left(\frac{dn}{dT} + (n-1)\,\alpha\right)\left(0.32\,\frac{J_{out}}{\rho C}\right)\frac{\langle\Delta T\rangle}{\langle\Delta T\rangle_{bulk}}$$

- For damage-limited extraction fluences and cool-down allowed from initial bulk temperature level to low RMS temperature ripple $\langle\Delta T\rangle$ just prior to next pulse
- Requires care in engineering diode light deposition profiles and radial absorption
- 2 micron wavelength has 1/2 $\langle\Delta\Psi\rangle$ as 1 micron for same output fluence and temperature ripple

Careful beam shaping and output-beam corrections allow use of output fluences above 10 J/cm^2

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FIG 19

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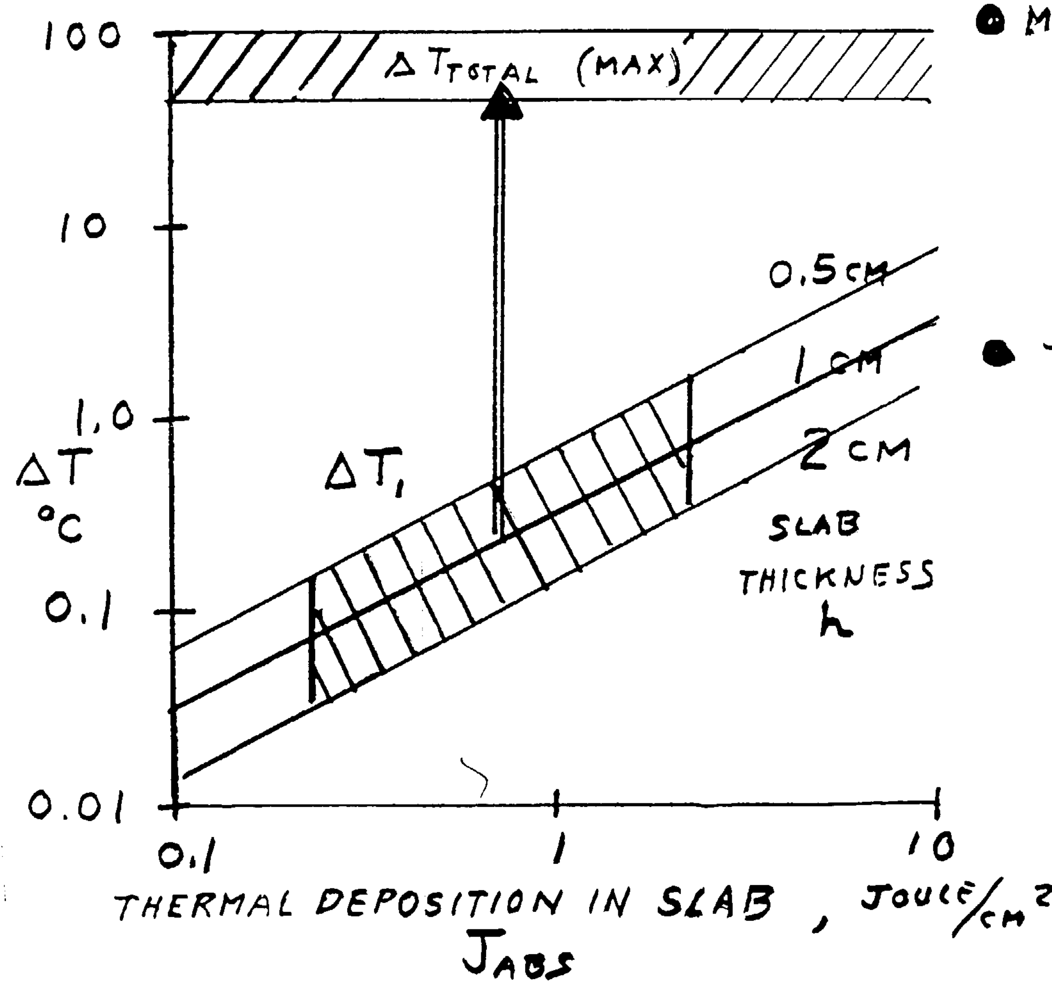
UNCOOLED-BURST OPERATION - A POSSIBLE NEAR-TERM DEMO

"HOT ROD" CONCEPT FOR NEAR-TERM DEMO OF SOLID-STATE LASER
- REF: BATTELLE COLUMBUS PROPOSAL / SMALL-SCALE DEMO
- REF: LLNL DESIGN / PROPOSAL TO P.L.'S ABL PROGRAM OFFICE



- MAX TOTAL ΔT FOR 10% GAIN LOSS

3.3% Nd_2O_3 LHG-5 GLASS

$T_{MAX} = 350°K \quad (g_0 = 0.01/cm)$

$T_{MAX} = 400°K \quad (g_0 = 0.05/cm)$

- TEMPERATURE RISE PER PULSE

$J_{ABS} = \rho C \, \Delta T_1 \, h$

> 100 - 1000 PULSE BURST
> WITHOUT COOLING
> ALLOWS POSSIBLE NEAR-TERM DEMO

FIG 20

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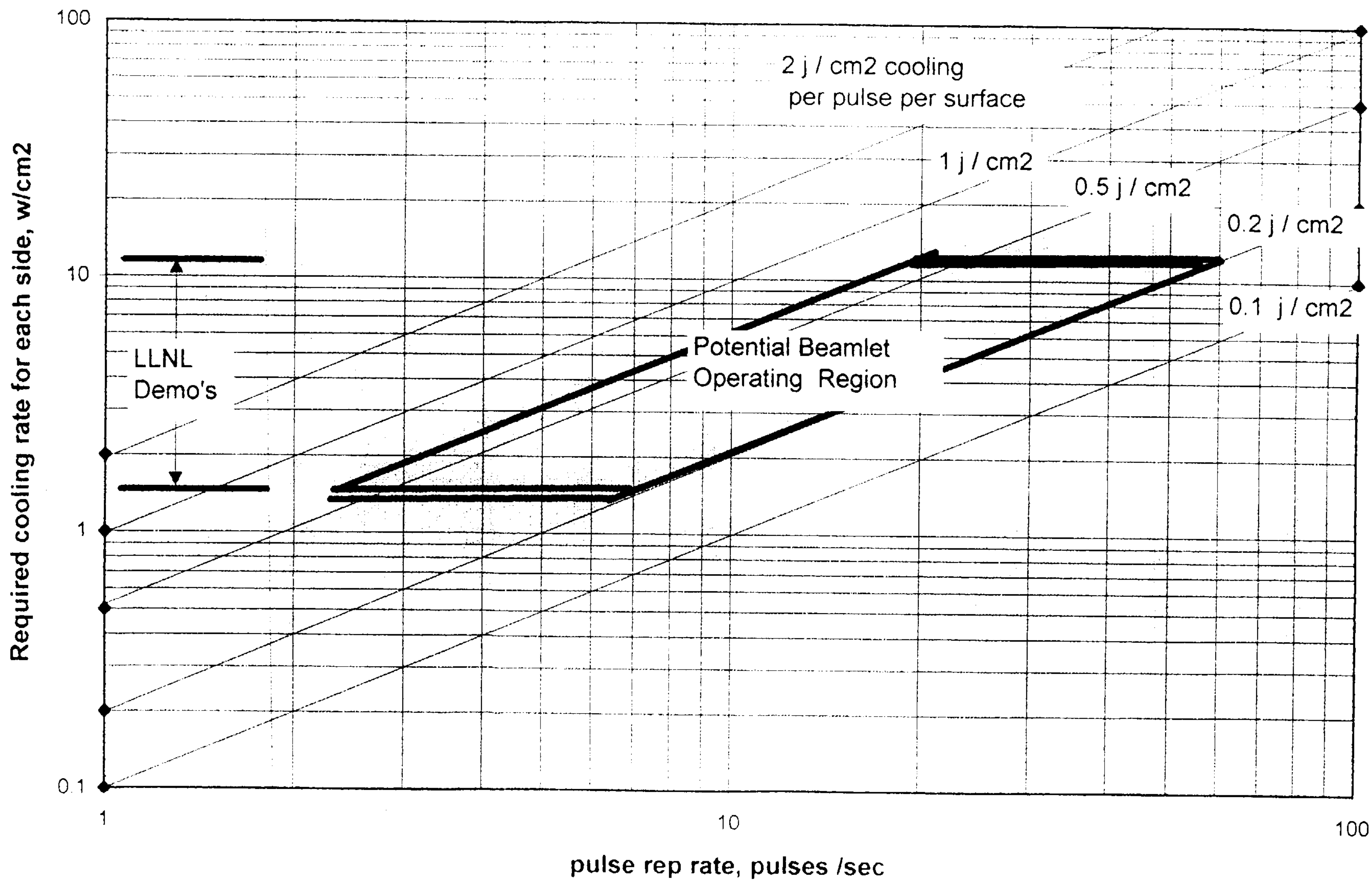
Required and Demonstrated Heat Transfer Rates



LLNL Demonstrated Cooling Rates and Energy Deposition Indicates 10 - 20 hz Appears Feasible

before gain reduction and other spectroscopic effects begin in the gain medium. At this point, optical pumping and lasing should be ceased, and cooling begun to return the medium to its original state. The analysis indicates that pump-nonuniformities and intrinsic gain medium nonuniformities will probably be the limiting causes of beam phase aberrations, as well as those in associated optical elements---all of which point to engineering design and perhaps adaptive optics to ameliorate those effects which cannot be eliminated by quality control and good engineering.

List of References

1. W. Koechner, "Solid State Laser Engineering", Springer-Verlag, 1976
2. G.Zeiders, "A Critique of High Rep-Rate Glass Lasers for ICF" , WJSA Report WJSA 77-15, TR1
3. C.Walters et al., "Nd-Glass Burst Laser with kW Average Power Output", IEEE Journal of Quantum Electronics, Vol. 31. No. Feb. 1995
4. J.Reilly, "Laser Transmitter Sizing and State-of the-Art Review", WJSA Report WJSA-R-93-B-001
5. G.Albrecht, "A 4 MJ Diode-Pumped, Heat Capacity Disc Amplifier - Defender" , briefing by LLNL , LLNL Document 99-50-0193, 12 GFA/fwh
6. A.Erlandson et al., "Model Predicting the Temperature Dependance of the Gain Coefficient and the Extractable Stored Energy Density in Nd:Phosphate Glass Lasers", J.Opt. Soc. Am. B / Vol 9, No. 2 / February 1992
7. S.Sutton et al, "Optimim Peformance Considerations for a Large-Aperture Average Power Solid-State Laser Amplifier", J.Appl.Phys, 69 (3), 1 February 1991

Attachment 3

Report Documentation Page

(Standard Form 298)

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ANALYSIS OF SOLID STATE MULTI-KILOJOULE REP-RATED LASERS IS PRESENTED IN ~~WHEN~~ OPERATED UNCOOLED. (NO ACTIVE COOLING DURING THE OUTPUT PULSE TRAIN). THE EMPHASIS IS ON OPERATION CONDITIONS WHERE PHASE HOMOGENEITY OF THE OUTPUT BEAM IS A MAXIMUM (NEAR DIFFRACTION LIMITED). PRACTICAL DESIGN CRITERIA ARE PRESENTED TO ALLOW SAFE, EFFICIENT, NEAR-DIFF'N-LIMITED BEAMS.

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